Hydrodynamics in Shallow Estuaries with Complex Bathymetry and Large Tidal Ranges

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LONG-TERM GOALS

Understanding the dynamics of flows, mixing and turbulence in estuaries with large tidal range and complex bathymetry. This includes making the connections between Lagrangian and Eulerian mean flow quantities as well as the role of fronts in determining overall estuarine structure. Of particular interest are (a) the dynamics of stratified turbulence in flows that are both strongly sheared and strongly stratified and (b) the effects of spatially varying bottom roughness on drag including directional sensitivity of bottom drag.

This work is important to modeling flows in complex estuaries found worldwide, e.g. on the Korean peninsula. By understanding the dynamics of these flows, necessarily limited observations can be integrated most effectively with numerical models in order to make predictions of environmental conditions likely to be encountered in naval operations.

OBJECTIVES

This work was a follow-on to the COHSTREX program involving researchers from the University of Washington and ourselves. Accordingly, the principal objective of this work was to use data collected during 2 major field campaigns in the Snohomish Estuary to understand the dynamics of the overall larger-scale flows in which the surface turbulence observations made by the APL group were embedded. In the end, our efforts focused on: (a) elucidating the overall dynamics of the Snohomish River Estuary (SRE), including the interaction between turbulence and stratification; (b) examining the dynamics of lateral fronts that developed and understanding their influence on overall structure of the velocity and salinity fields; (c) examining the dynamics of the residual flows accounting for the large tidal range; and (d) determining how the fine-scale variability of the depth associated with sand wave fields of various wavelengths, heights and orientations affects bottom drag.

APPROACH

Our project exclusively involved retrospective analysis of data collected during the COHSTREX program. Sarah Giddings worked on the first three areas above as part of her thesis (completed in Dec

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2010). This included developing momentum and salt budget for different regions in the flow as well as computing various quantities in sigma as well as Cartesian coordinates. The front work included integration of data from our REMUS AUV, boat transecting and fixed instruments. Derek Fong worked with integrating fixed ADCP data, including single-ping derived turbulence data, with multi-beam sonar-derived bathymetry in order to address connections between properties of the bottom roughness (e.g. spectral distribution of height) with observed spatial and temporal variations in bottom drag coefficient, C_D.

WORK COMPLETED

All analysis of data is complete and current efforts now focus on publication of the results. Sarah Giddings' thesis was submitted in December 2010. Several of the papers describing this work are currently in revision.

RESULTS

In-situ observations in the SRE reveal complex intratidal and fortnightly stratification, mixing, and dispersion dynamics. Both salt-wedge propagation and concomitant straining of the density field dominate temporal and spatial variations in stratification leading to intratidal variability of shear and mixing that differs in important ways from observations in partially-mixed estuaries. During much of the tidal cycle, the system experiences active buoyancy affected turbulence. Bottom generated turbulent kinetic energy production is enhanced during spring tides and acts in concert with straining to counteract advection and minimize vertical stratification during the spring flood tides. This bottom-generated mixing contributes to a buoyancy flux near the top of a well-mixed layer during strong flood tides. During strong ebb tides, interfacial shear production and buoyancy flux occur along the sharp straining-enhanced interface just before the system becomes well-mixed. Longitudinal dispersion is less sensitive to the spring/neap cycle yet exhibits strong intratidal variability, with enhanced longitudinal dispersion observed during large ebbs, behavior that can be attributed to reversible straining by vertical shear. Overall, ebb-tide advection and straining enhances stratification, shear, and longitudinal dispersion and allows for interfacial mixing. This interfacial mixing subsequently limits the magnitude of ebb tide longitudinal dispersion. Intratidal variability, which varies on the spring/neap scale, is a dominant feature of this estuary, suggesting the importance of intratidal processes and tidally varying mixing coefficients in similar strongly stratified, strongly forced estuaries.

Local alterations to this intratidal variability result from shoal/channel interactions. Complex bathymetry and a large tidal range in the Snohomish River Estuary lead to trapping of mid-density water over intertidal mudflats. The convergence of this water mass with dense water in the main channel forms a sharp front. Our use of different kinds of sensors (e.g. thermal imnaging, fixed ADCPs etc.) allowed detailed observations of the frontal dynamics. The frontal density interface is maintained via convergent transverse circulations driven by the competition of lateral baroclinic and centrifugal forcing. Local spatial and temporal variations in stratification and vertical mixing result from the frontal presence and propagation. Importantly, this front leads to enhanced stratification and suppressed vertical mixing at the end of the large flood tide, in contrast to what is found in many estuarine systems. This front does not significantly alter longitudinal dispersion; however, similar trapping-driven fronts may contribute to longitudinal dispersion in estuaries with larger trapping regions. The mechanism observed fits within the broader context of bathymetrically driven frontogenesis mechanisms in which varying bathymetry drives lateral convergence and baroclinic

forcing. Similar dynamics are expected to occur in similar shallow, macrotidal estuaries with complex geometry, as well as estuaries with broad intertidal regions, shallow regions, or subembayments.

These intratidal dynamics influence residual (subtidal or tidally averaged) circulation in this system. Residual circulation profiles in estuaries with a large tidal amplitude to depth ratio often are quite complex and do not resemble the traditional estuarine gravitational circulation profile (up-estuary at the bed, down-estuary at the surface). Our analysis shows that a sigma coordinate system allows for a more reasonable examination of residual circulation profiles than a fixed vertical coordinate system, permitting empirical orthogonal function analysis and computation of a tidally averaged momentum balance. This analysis shows that the residual circulation profiles in fixed vertical coordinates result from a combination of a traditional gravitational circulation shaped profile with a reverse circulation driven by the nonlinearity of the propagating barotropic tide. The depth-normalized coordinate system exhibits residual profiles that are similar to traditional estuarine theory. This two-layer exchange flow is enhanced when a Stokes wave transport velocity is incorporated, which is upstream at all depths. However, as common in many estuaries, the residual shear is not driven solely by the mean longitudinal density gradient. Rather, residual circulation in this system is driven by asymmetries during the tidal cycle, particularly straining and advection of the salinity field and local effects from lateral advection in the frontal region.

Finally, almost all field scale numerical simulations of environmental flows rely on a parameterization of the bed stress in terms of either a coefficient of drag CD, or roughness height z_0. In most cases, these parameters are assumed to be constant in both time and space. Recent observations presented here suggest that this may be a poor assumption in many river and estuarine systems. Our direct measurements of turbulent stresses over a relatively small area in the SRE, a tidally forced river, suggest that there may be significant temporal and spatial variability in bed stress, and consequently, appropriate bottom drag parameterization. We find observed variability is due to both bedform amplitude and spatial scales of variability: measurements at four sites with a 1 km stretch of the SRE exhibit CD variations of a factor of two, dependent on both direction of the currents and location. This suggests that both bottom stress implementation and bathymetric resolution need serious consideration in accurate modeling of field scale environmental flows.

IMPACT/APPLICATIONS

This work implies that further effort at understanding the connections between small-scale variability in bottom bathymetry ("aka "roughness") may be important to computing flows on the sub 100m scale in tidal systems. Approaches integrating multi-beam sonar for bottom mapping with maps of spatially variable surface turbulence as might be derived from thermal imaging based PIV as well as bottom stress information derived from acoustic instruments like ADCPs and ADVs would seem best suited for making further progress in this direction.

RELATED PROJECTS

None currently

PUBLICATIONS

Giddings, S.N., D.A. Fong, and S.G. Monismith "Circulation and mixing in a shallow, macrotidal estuary." J. Geophys. Res., (Oceans) 116, C03003, doi:10.1029/2010JC006482, 2011

Wang, B., S. N. Giddings, O.B. Fringer, E.S. Gross, D.A. Fong, and S. G. Monismith, "Modeling and understanding turbulent mixing in a macrotidal salt wedge estuary," J. Geophys. Res. (Oceans) 116, C02036, doi:10.1029/2010JC006135, 2011

Giddings, S.N., "Dynamics of a shallow, macrotidal, strongly stratified estuary," PhD thesis, Stanford University, December 2011, 231 pp.

Walter, R. K., N.J. Nidzieko, and S.G. Monismith, "Similarity Scaling of Turbulence Spectra and Cospectra in a Shallow Tidal Flow," J. Geophys. Res. (Oceans) (in press)

Giddings, S.N., D.A. Fong, and S.G. Monismith, C. C. Chickadel, K. A. Edwards, W. J. Plant., B. Wang, O. B. Fringer, A. R. Horner-Devine, and A. T. Jessup, " Frontogenesis and frontal progression of a trapping-generated estuarine convergence front and its influence on mixing and stratification." Estuaries and Coasts (submitted).

Fong, D.A. , S. N. Giddings, and S.G. Monismith, "Temporal and spatial drag coefficient variability in a tidally-forced flow over varying bed roughness, " Geophys. Res. Letters (submitted – in revision for publication elsewhere)

HONORS/AWARDS/PRIZES

Donald W. Pritchard Award for Estuaries and Coasts Geophysics Paper - "Thermal variability in a tidal river"

Coastal and Estuarine Research Federation

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